

ELEVATED TEMPERATURE FATIGUE-CREEP
BEHAVIOR OF NICKEL-BASE SUPERALLOY IN 625

by

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KEYWORDS

Continuous cycling, fatigue-creep, tension/compression hold time,
Inconel 625.

ABSTRACT

A research program has been carried out to establish the low-cycle fatigue and creep-fatigue behaviors of Inconel 625 at elevated temperatures (650 and 815°C).

The main observations were related to the effect of temperature and of hold times. Under continuous cycling, a temperature increase from 650 to 815°C caused a reduction in the fatigue life by a factor of 2 at a high strain, and by a factor of 3 at a low strain.

Tension hold times had little detrimental effect on cyclic life at 650°C concerning the life reduction with respect to continuous cycling; at 815°C, on the other hand, this became more significant. Compressive hold times also had a damaging effect on the fatigue life, and this was larger than that associated with tensile hold times; in particular, it was very pronounced for low strain levels at 815°C.

An analysis of data using a life prediction method previously suggested for creep-fatigue combination loadings has also been carried out. The method takes into account the damaging effect due to a compression hold time separately from that due to a tensile hold time in interspersed creep-fatigue loadings. The overall correlation between theoretical calculations and experimental results is reasonably good, for strain levels ranging from 1.2% to 0.4%.

INTRODUCTION

Superalloy IN 625 is a potential candidate material for use in structural components subjected to cyclic loadings at high temperatures, such as parts of jet engines and nuclear reactors [1]. To the authors' knowledge, little information concerning the material behavior under these loading conditions is presently available; in particular, the scarceness of experimental data under creep-fatigue combination loadings makes the use of this material in component design difficult.

The present research program has been carried out to provide the mechanical properties on the low-cycle fatigue and creep-fatigue behavior of Inconel 625 at elevated temperatures (650 and 815°C). Under continuous cycling, the data base of the material is established; the influence of hold-times introduced in each cycle (interspersed creep-fatigue) on the material life is then examined.

A life prediction procedure recently suggested [2,3] has been applied to the data obtained under cyclic loading, with and without hold times. The main characteristic of the approach stems from a combination of two stress-(or strain-)dependent damage concepts (for fatigue and for creep), which takes into account the stress relaxation behavior during the hold period. The overall correlation between isothermal experimental results and theoretical predictions is discussed.

EXPERIMENTAL PROCEDURE

Superalloy In 625 is a nickel-chromium alloy strengthened by an addition of molybdenum. The nominal chemical composition of the material studied is given in Table 1.

Smooth cylindrical test specimens with uniform gage length of 6.35 mm in diameter conforming to ASTM E606-77 recommendations, were used in this experimental work which was a joint effort conducted in two laboratories, one at Ecole Polytechnique, the other at IMR Institute.

All fatigue tests were carried out under uniaxial, strain-controlled conditions using a servohydraulic closed loop testing machine. Strains were measured by an axial extensometer and the load measurements were obtained by means of a load-cell in series with the specimen. Stress-strain hysteresis loops were recorded at predetermined cycles throughout the life of the specimen.

The specimen was heated by an electrical resistance furnace with three separately controlled heating zones providing a uniform temperature distribution over the specimen gage length. The test temperature was controlled within $\pm 2^{\circ}\text{C}$.

The loading waveform was generated by a computer which also assumed data acquisition during the tests. All tests were performed in air under isothermal conditions, at 650 and 815°C;

strain ranges between 0.4% and 1.2% were considered. For continuous cycling tests, a triangular waveform with zero mean value and with a constant strain rate ($1 \times 10^{-2} \text{ s}^{-1}$) was used. In interspersed creep-fatigue tests (cyclic loading with hold time in each cycle), tensile or compressive dwell periods of 1, 2, 5, 10, 15 and 30 minutes were imposed in each cycle at peak strain. Failure was defined as a reduction of the stabilized maximum cyclic stress by 50%.

TEST RESULTS

Continuous cycling

A summary of the experimental results obtained under continuous cycling is given in Table 2 and the diagram of the total strain range $\Delta\epsilon$ in terms of the number of cycles at failure N_0 is shown in Fig.1. The results show that a temperature increase from 650 to 815°C causes a reduction in fatigue life by a factor of 2 at a high strain and by a factor of 3 at a low strain.

The variation of the stress range $\Delta\sigma$ versus the number of applied cycles n , obtained at different strain ranges, is shown typically in Fig.2. Under continuous cycling, it appears that the material cyclic characteristic depends significantly upon the temperature; in fact, for a high strain level, at 650°C, a strain hardening behavior was observed, while at 815°C a reverse trend (strain softening) was noted. In contrast, at a low strain range, the material exhibited a relatively stabilized cyclic behavior at

both temperatures.

It is also noted that IN 625, when subjected to continuous cycling, developed a relatively small compressive mean stress (less than 6% of the stress range).

Interspersed creep-fatigue tests

The results of the interspersed creep-fatigue tests at two temperatures are summarized in Table 3. On the basis of a limited number of test results, the following observations can be made:

- a) ~~IN 625~~ exhibited a particular stress relaxation behavior during a tension hold time, as shown in Fig.3. The stress relaxation rate was relatively high at the beginning of the hold period and the tensile stress reached a saturation level rapidly. Furthermore, the temperature has a very strong effect on this relaxation rate. In fact, after an elapsed time equivalent to 10% of the total hold period, the maximum stress was relaxed by 25% at 650° and by 90% at 815°C. This particular characteristic is reflected on the material life subjected to creep-fatigue loading.

The stress relaxation behavior during compression hold times was similar to that observed during tension hold times.

- b) In general, the variation of the stress range $\Delta\sigma$ with applied cycles n , in tests with a tensile hold time, follows a

pattern comparable to that already shown for tests without a hold time. However, the stabilized stress range (usually considered at half life) may depend upon the hold time periods, as shown in Fig. 4. It is also noted that the effect of the hold time period on the stabilized stress range increases with a decrease of the imposed strain level for both temperatures; however, the trend of variation is quite different for a low strain range: with an increase of tension hold time t_d , $\Delta\sigma$ increases at 650°C, whereas it decreases at 815°C. Further investigation may be necessary for explaining this material characteristic.

Examination of the hysteretic behavior of this material reveals that, during hold time tests, a mean stress opposite the hold direction was developed. This mean stress, already reported for several nickel-base superalloys [4-7], is usually attributed to the rapid stress relaxation occurring during hold times. The cyclic stress is driven in a direction opposite the hold direction and this leads to a tensile mean stress under compressive holds and a compressive mean stress under tensile holds. As typically observed in the case of high strength and ductility materials [6], the magnitude of the mean stress for IN 625 is larger at lower strain levels.

- c) Tension hold times (t_d) have little detrimental effect on cyclic life at 650°C with respect to continuous cycling (Fig. 5a). At 815°C however, the effect of tension hold times becomes more significant (Fig. 5b); for example, with $t_d = 15$

min. at the latter temperature , the life is reduced by a factor of 2 at $\Delta\epsilon = 1\%$ and by a factor of 5 at $\Delta\epsilon = 0.6\%$.

Compressive hold times (t_c) also have a damaging effect on fatigue life, larger than that associated with tensile hold times; furthermore, at 815°C this effect is very pronounced for low strain levels , as shown in Fig.5b. As an example, at this temperature and at $\Delta\epsilon = 0.6\%$, a tension hold of 5 min. reduced the fatigue life significantly (in the present observation, by a factor of 7) as compared to that observed under continuous cycling; this factor is approximately doubled for a 5 min. hold in compression. The significant detrimental effect of compression hold times has been noted for many materials, particularly for nickel-base superalloys [5-11].

In the investigation of the material creep-fatigue behavior, one of the primary objectives of the study was to analyse the experimental results using a potential procedure for life prediction. This is explored in the following section.

APPLICATION OF THE PROCEDURE FOR LIFE PREDICTION

Among many methodologies proposed in recent years for life prediction from an engineering point of view, the continuous damage approach suggested by Bui-Quoc and Biron [2,3] takes into consideration the order effect of loading under pure fatigue, under pure creep, under a fatigue-creep sequence and under interspersed

creep-fatigue . This method was recently applied for the analysis of the behavior of stainless steels [12], Alloy 800 [13] and 2 1/4 Cr-1 Mo steel [11] under cyclic loading conditions including tension and compression hold times at temperatures up to 760°C.

The procedure is now applied to the present data under cyclic loading with and without hold time. Only the essential features of the concept are given here since the details of the development and the physical interpretation of different parameters can be found in [12,13].

FATIGUE LOADING

In pure fatigue, the damage has been based on the reduction of the fatigue limit due to damage accumulation. The development has led to an analytical expression for describing the basic fatigue curve in a $\Delta\epsilon - N_0$ (total strain range versus number of cycles at failure) diagram. Under isothermal strain-controlled continuous cycling conditions, the analytical curve may be described by [3]:

$$N_0 = \frac{K_f}{\gamma^a} \left[\frac{1}{\gamma - 1} - \frac{1}{\gamma - (\gamma/\gamma_u)^B} \right] \quad (1)$$

In eq. (1), the strain parameters γ and γ_u are expressed in terms of the total strain range $\Delta\epsilon$ as follows:

$$\gamma = 1 + \ln (\Delta\epsilon / \Delta\epsilon_0) \quad (2a)$$

$$\gamma_u = 1 + \ln (2\epsilon_u / \Delta\epsilon_0) \quad (2b)$$

where $\Delta\epsilon_0$ is the fatigue limit strain range of the original material and ϵ_u is the true strain at fracture in a short-term tensile test at the temperature and the strain rate imposed in continuous cycling. Also in eq. (1), K_f and a are material constants which may be determined by referring to two data points in the $\Delta\epsilon-N_0$ diagram. Fig.1 also shows the behavior of eq. (1) together with the experimental results of IN 625 at the two temperatures considered.

The normalized damage due to fatigue has then been defined in terms of the instantaneous fatigue strength (instantaneous fatigue limit); this has led to the strain-dependent fatigue damage function D_f as follows [3]:

$$D_f(\gamma, \beta_f) = \frac{\beta_f}{\beta_f + (1 - \beta_f) \left[\frac{\gamma - (\gamma/\gamma_u)^B}{\gamma - 1} \right]} \quad (3)$$

where β_f is the life fraction (ratio between number of applied cycles n and number of cycles to failure N_0). An inverse relation of β_f in terms of D_f , i.e. $\beta_f = \beta_f(\gamma, D_f)$, may also be obtained.

CREEP LOADING

In pure creep, the damage has been characterized, in a similar manner, by the reduction of the creep strength σ_p (material strength related to the creep process) due to damage accumulation. The development, in this case, has led to an expression which describes the basic isothermal creep-rupture curve in a $\sigma - T$ (σ :

stress, T : time at rupture) diagram as follows [3]:

$$T = \frac{K_c}{\theta^b} \left[\frac{1}{\theta - \theta_p} - \frac{1}{\theta^d - \theta_p} \right] \quad (4)$$

In eq. (4), the dimensionless stresses θ and θ_p are defined as follows:

$$\theta = \sigma / \sigma_u \quad \text{and} \quad \theta_p = \sigma_p / \sigma_u \quad (5)$$

with σ_u being the ultimate tensile stress. The values of $\theta_p = 0.05$ and $d = 0.5$ have been suggested in previous investigations [14] and will also be used in the present work. Material constants K_c and b may be evaluated by considering two reference data points in a σ - T diagram. The isothermal creep-rupture data of IN 625 for two test temperatures [15] is reproduced in Fig.6 together with the analytical curves obtained from eq. (4).

The normalized damage D_c due to creep has then been defined in terms of the instantaneous creep strength, leading to the following relation [3]:

$$D_c(\theta, \beta_c) = \frac{\beta_c}{\beta_c + (1 - \beta_c) \left[\frac{\theta - \theta_p}{\theta^d - \theta_p} \right]} \quad (6)$$

where β_c is the life fraction (ratio between exposure time t and time at rupture T). The reverse relation $\beta_c = \beta_c(\theta, D_c)$ may also be obtained.

For each type of loading, with the damage functions obtained from the basic theory, the concept takes into account the sequence effect of loading in multistep tests in a manner consistent with the trend generally observed in experiments.

The analytical results of eq. (1) and eq. (4) will be used to characterize respectively the fatigue and creep damages in combined fatigue-creep evaluation.

INTERSPERSED FATIGUE-CREEP

The procedure for predicting the material life under combined creep-fatigue loading is formulated in a straightforward manner by combining the two damage functions. In order to take into account the strong sequence effect, such as observed on Alloy 800 and 304 SS, an interaction parameter, identified as w , has been introduced in whichever damage function is considered as the second process [12,13]. For example, for the creep process, the damage function with interaction D_c' is similar to D_c except that β_c is replaced by β_c^w ; thus $D_c' = D_c(\theta, \beta_c^w)$.

a) Evaluation procedure

Under interspersed creep-fatigue, the procedure of damage evaluation is schematically illustrated in Fig.7. At stage J , damage D_J is equal to that accumulated in the previous cycles. The cycle ratio β_J is given by $\beta_J = \beta_f(x, D_J)$ and D_K is calculated

from eq. (3), i.e. $D_K = D_f[\gamma, (\beta_T + \Delta\beta_f)]$ where $\Delta\beta_f = 1/N_0$ with N_0 being obtained from eq. (1).

A similar procedure is applied for the creep portion of the cycle, as illustrated also in Fig.7. In particular, the equivalent cycle ratio $\Delta\beta_c$ is calculated on the basis of the relaxation stress characteristics observed during the hold period, i.e. $\Delta\beta_c$ due to creep during a tensile hold time t_d and a compressive hold time t_e in a cycle is assumed to be governed by:

$$\Delta\beta_c = \Delta\beta_d + (H_d + H_e) (\Delta\beta_e)^\alpha \quad (7)$$

where
$$\Delta\beta_d = \int_0^{t_d} \frac{dt}{T} \quad \text{and} \quad \Delta\beta_e = \int_0^{t_e} \frac{dt}{T} \quad (8)$$

Material constants H_d and H_e are associated with tension and compression hold times. If a particular hold time is not imposed, the associated constant takes the value of zero.

Failure is assumed to occur when the accumulated damage equates unity.

With the interaction consideration, the procedure is essentially the same, except that the modified creep damage function D_c' , instead of D_c , is used.

b) Stress relaxation behavior

During the tensile strain hold period, the stress σ decreases from σ_m (at the beginning of the hold) to σ_d (at the end of the

hold) as shown in Fig.8a for a tensile hold condition. This stress characteristic may be adequately described by [16]:

$$\ln(\sigma_m / \sigma) = A (t^*)^p \quad (9)$$

where
$$t^* = (\Delta\epsilon / 2m)^{2m} t \quad (10)$$

m is the monotonic strain hardening exponent. A and p are material constants independent of the strain level and the hold period; these constants may be obtained from a plot of the experimental data corresponding to the limiting condition of eq. (9); i.e. $\ln(\sigma_m / \sigma_d)$ versus t_d^* , where t_d^* is calculated from eq. (10) with $t = t_d$.

As an approximation, σ_m may be taken as the cyclic stress amplitude ($\Delta\sigma/2$) obtained in continuous cycling at the same strain range and strain rate at the stabilized condition. The error on the calculated lives due to this approximation, as discussed in [12], is quite acceptable for many cases. The parametric correlation between $\Delta\sigma$ and $\Delta\epsilon$, as suggested in [11] is used again for IN 625:

$$\frac{\sigma_m}{Y} \approx \frac{\Delta\sigma}{2Y} = k + m' \ln\left(\frac{\Delta\epsilon}{2\epsilon_Y}\right) \quad (11)$$

where ϵ_Y is the ratio between the yield strength Y and the elastic modulus E ; k and m' are temperature dependent material constants evaluated from a plot of the experimental data as shown in Fig. 9.

c) Life-time calculation with tension hold times only ($t_h = 0$)

For this case, $\Delta\beta_c = \Delta\beta_d$ and is evaluated using eq. (8) in connection with the relaxation stress characteristics. Then, the procedure outlined in a) can be followed.

The interaction parameter w can be precisely evaluated only with experimental data from fatigue/creep or creep/fatigue sequences [13]. In the absence of this type of data, w may be determined by referring to a data point at a particular value of $\Delta\epsilon$ and a given value of t_d [12]. For example, for the present data, by referring to the test result at 815°C at $\Delta\epsilon = 1.0\%$ and $t_d = 15$ min., this parameter is very close to 1.0. This means that, when the presently suggested procedure is used for the analysis of the behavior of IN 625 material, the interaction effect between the two processes is negligible. In subsequent calculations, $w = 1.0$ is therefore assumed, and the calculated lives of IN 625 with different values of t_d are shown in Fig.5. The overall agreement between the calculated and observed lives is acceptable. In particular, at 815°C, the additional theoretical detrimental effect due to $t_d = 30$ minutes is small in comparison with the condition associated with $t_d = 15$ min.; for example, at $\Delta\epsilon = 1.0\%$, a tension hold time of $t_d = 15$ min. reduced the fatigue life by a factor of about 2.0 with respect to continuous cycling; with $t_d = 30$ min., the additional reduction in life is negligible. This characteristic is obtained as a result of a rapid stress relaxation at the beginning of the hold period to a saturation stress at a very low level, as mentioned in the previous sections. Since the relaxation

characteristics are taken into account in the evaluation of the creep-fatigue behavior, the analytical predictions correctly reflect the experimental data as shown in Fig.5.

d) life-time calculation with compression hold times only

($t_d = 0$)

Under cyclic loading with a compression hold time only, IN 625 exhibits a damaging effect, and eq. (7) is reduced to $\Delta\beta_c = H_e (\Delta\beta_e)^\alpha$. With the results of two tests with two different values of $\Delta\epsilon$, constants H_e and α may be evaluated. For the present material, $H_e = 0.31$ and $\alpha = 0.65$.

The correlation between the calculated lives and the available test results are shown in Fig.5b for 815°C. For a given hold period, the compression hold times are theoretically more detrimental than the tension hold times. For example, at $\Delta\epsilon = 0.6\%$, a compression hold time of 5 min. reduced fatigue life 18 times with respect to continuous cycling; this factor is about 5 for a tension hold time of 15 min. This is in agreement with the experimental results.

DISCUSSION

For the present material, a tensile hold time larger than 5 min. introduced in each cycle causes a reduction of the life; this reduction is quite small at 650°C and more significant at 815°C. This may be explained by the reduction of effectiveness of the strengthening mechanisms, as usually observed in nickel-based superalloys at relatively high temperatures [17].

In spite of a limited number of experimental data, it may be pointed out that under creep-fatigue loading with a tensile hold time only, IN 625 exhibits a damaging effect much smaller than stainless steels and Alloy 800. For example, in the temperature range 650 to 815°C, with $\Delta\epsilon = 1\%$ and $t_d = 30$ min., the typical factor of reduction of material life is 2 for IN 625, 4 for Alloy 800, 5 for 304 stainless steel and 10 for 316 stainless steel. On the other hand, IN 625 incurs a more damaging effect with a compression hold time than with a tensile hold time. This behavior is in contrast to that observed in the study of the three other materials; in addition, these latter materials exhibit a healing effect when subjected to a tension-compression hold time as compared to a tension hold time only. These characteristics have been taken into consideration in the development of the life prediction procedure. The overall correlation between calculated lives and the reported data is reasonably good.

As mentioned earlier, the life calculations with a hold time have been carried out using a maximum cyclic stress σ_m identical to that obtained under continuous cyclic loading ($\sigma_m = \Delta\sigma/2$). For

some materials such as stainless steels, experimental results have shown that σ_m decreases with an increase of the hold period and this variation is more pronounced for a high strain than for a low strain. Nevertheless, the life predictions obtained using the actual and the approximate maximum stresses were both acceptable (with the approximate maximum stresses, the predicted lives stand on the conservative side), as already discussed in [12]. In the case of IN 625, due to a rapid stress relaxation during hold times, no significant difference between stress ranges in tests with and without hold times was observed; however, due to this rapid relaxation, a mean stress opposite to the direction of the hold period occurred.

An attempt has been made to compare the predicted lives already presented in the previous sections with those obtained using the actual maximum stresses. Typical results of calculations for IN 625 are given in Table 4. For a given strain level, since the actual maximum stress is reduced due to the mean stress opposite in sign, it is expected that the predicted lives should be larger when the actual experimental maximum cyclic stresses are used. It should be noted that, if the actual maximum cyclic stresses are used to compute the equivalent time ratio due to creep during the hold time, complete experimental results (i.e. for a given temperature, tests with different strain levels combined with different hold periods) must be made available. This gives a realistic material behavior, but it also involves extensive testing. The use of the maximum cyclic stress based on the stress range under continuous cycling simplifies the procedure and gives

predictions smaller (on the conservative side) than those obtained with the actual maximum stress.

CONCLUSION

Continuous cycling and hold time tests were performed on Inconel 625 at 650 and 815°C in order to obtain the basic low-cycle fatigue properties for the material and to assess the influence of the time-dependent damage. Experimental results indicated that the temperature and the hold time both had a significant effect on fatigue life of IN 625.

a) Under continuous cycling, IN 625 cyclically hardened at 650°C and softened at 815°C at high strain ranges; at low strain range levels, however, it showed a relatively stable behavior throughout its life in the considered temperature range.

b) During hold times, the stress relaxed rapidly after a short period and remained relatively unchanged thereafter. The period at which the stress relaxation rate stabilized was dependent upon the temperature: at 815°C, this period was about 3 minutes for all strain ranges investigated, whereas, at 650°C, it increased with the strain range; typically, it was 3 min. at $\Delta\epsilon = 0.8\%$ and 15 min. at $\Delta\epsilon = 1.2\%$.

c) At 815°C, compression hold times introduced in each cycle caused more damage than tension hold times; a drastic reduction of life due to hold times at peak compressive strain was observed at low strain ranges.

d) An analysis of data using a life prediction method previously

suggested for the creep-fatigue combination loadings was carried out. In order to take into account the damaging effect due to a compression hold time separately from that due to a tensile hold time, a generalized relation has been introduced for the equivalent time ratio associated with the creep process. The overall correlation between theoretical calculations and experimental results was reasonably good, particularly for interspersed fatigue-creep loadings with tension or compression hold times at strain levels approximately ranging from 1.2% to 0.4%. A rough evaluation of the numerical values of the material constants has been made, based on limited experimental results.

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TABLE 1 Chemical composition of Inconel 625 (% weight)

C	Mn	Fe	S	Si	Al	Ti	Mo	Cb-Ta	Cr	Ni
0.05	0.25	2.5	0.008	0.25	0.2	0.2	9.0	3.65	21.5	Bal

TABLE 2 Continuous cycling LCF results of Inconel 625

Specimen #	Strain range (%)			Stress (MPa)*		Cycles to failure N _o
	total $\Delta\epsilon$	plastic $\Delta\epsilon_p$	elastic $\Delta\epsilon_e$	maximum σ_m	minimum σ_{min}	
T°C = 650°C						
54	0.55	0.013	0.537	459	-472	29,000
55	0.78	0.130	0.650	553	-559	6,780
46	0.99	0.320	0.670	584	-598	940
29	1.19	0.400	0.790	666	-700	800
64	0.60	0.024	0.576	531	-477	16,942
T°C = 815°C						
32	0.37	0.021	0.349	253	-239	57,342
25	0.6	0.063	0.537	387	-402	5,450
24	0.8	0.224	0.576	395	-496	1,374
34	1.0	0.360	0.640	464	-477	560
23	1.0	0.407	0.593	460	-463	421
44	1.2	0.585	0.615	466	-474	455
45	1.2	0.595	0.605	457	-465	315

* Conversion factors: 1 Ksi = 6.89 MPa

TABLE 3 Hold time fatigue test results

Specimen #	Hold time* (minutes) t_d t_e		Strain range (%)			Stress (MPa)*			Relaxed stress (MPa)**	Cycles to failure N	Time to failure (hours) t_f
			total $\Delta\epsilon$	plastic $\Delta\epsilon_p$	elastic $\Delta\epsilon_e$	maximum σ_m	minimum σ_{min}	mean σ_{mean}			
T° = 650 °C											
59	10	0	1.0	0.3	0.7	536	-846	-155	154	1,092	183
40	30	0	1.2	0.447	0.753	599	-863	-132	208	712	356
T° = 815 °C											
58	5	0	0.6	0.26	0.340	250	-456	-103	211	722	60
60	15	0	0.62	0.31	0.310	233	-405	-86	210	1,041	261
51	15	0	0.82	0.428	0.392	332	-499	-83.5	297	437	109
49	15	0	1.02	0.605	0.415	371	-801	-65	332	262	66
36	1	0	1.22	0.777	0.443	469	-520	-25.5	332	220	4
30	10	0	1.21	0.633	0.577	431	-566	-67.5	346	310	52
38	10	0	1.22	0.846	0.374	388	-454	-33	308	349	58
33	15	0	1.22	0.777	0.443	441	-543	-51	357	210	53
37	15	0	1.22	0.800	0.420	432	-526	-47	356	223	56
27	30	0	1.22	0.800	0.420	441	-536	-47.5	388	170	85
75	0	5	0.39	0.086	0.304	443	-142	-150.5	101	880	74
71	0	5	0.61	0.290	0.320	493	-358	-67.5	482	310	26
68	0	5	0.65	0.289	0.361	489	-337	-76	271	430	36
69	0	15	1.10	0.706	0.394	506	-427	-39.5	384	250	63

* t_d : tension hold time t_e : compression hold time

**Conversion factor: 1 Ksi = 6.89 MPa

Table 4 Comparison of predictions obtained with the approximate and the actual stresses.
IN 625, 815°C, $t_d = 15$ min, $t_e = 0$

$\Delta\epsilon$ (%)	Experimental results (cycles) "A"	PREDICTIONS (CYCLES)			
		Using approximate maximum stress ($\sigma_m = \Delta\sigma/2$) "B"	"B" —— "A"	Using actual maximum stress "C"	"C" —— "A"
1.2	210	207	0.98	236	1.1
1.0	262	325	1.2	443	1.7
0.8	437	560	1.3	917	2.1
0.6	1041	1300	1.2	3183	3.0

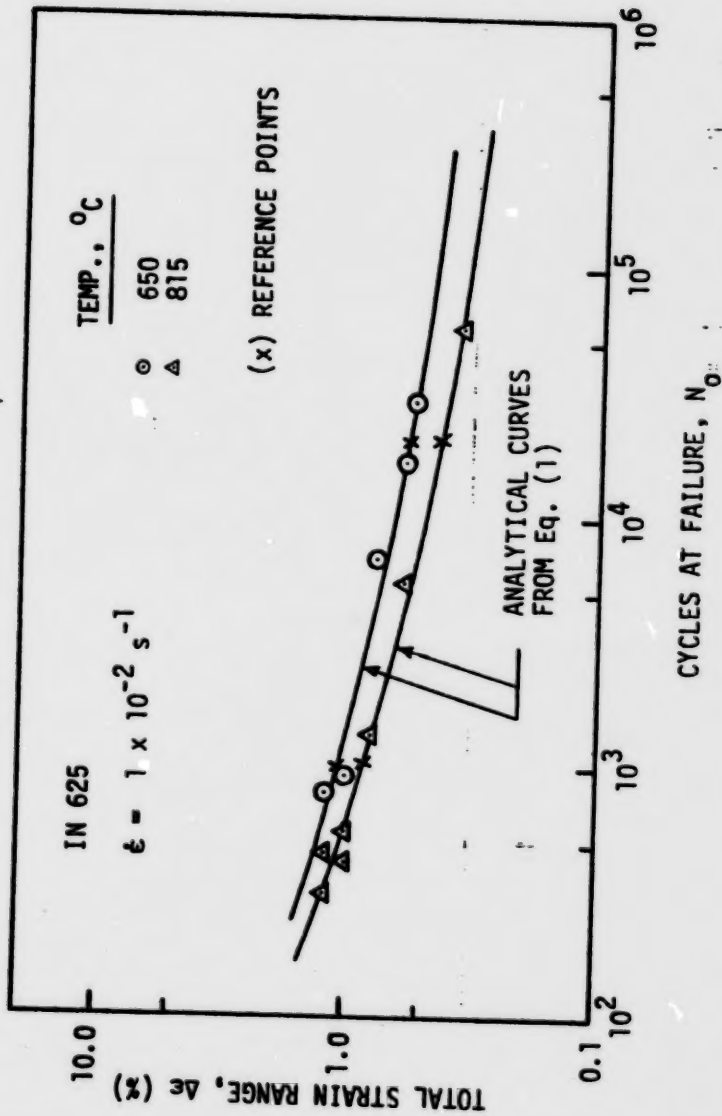


Fig. 1

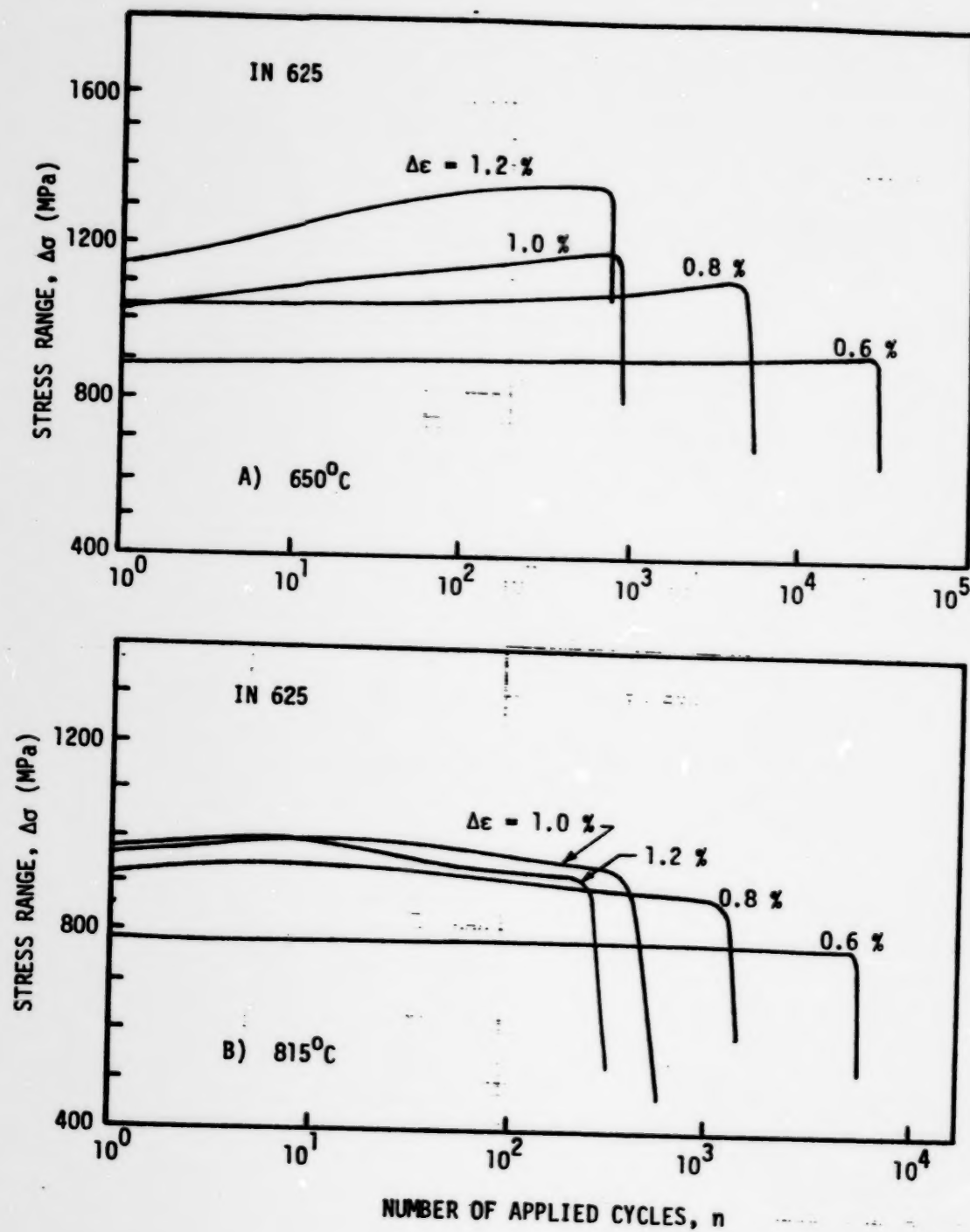


Fig. 2

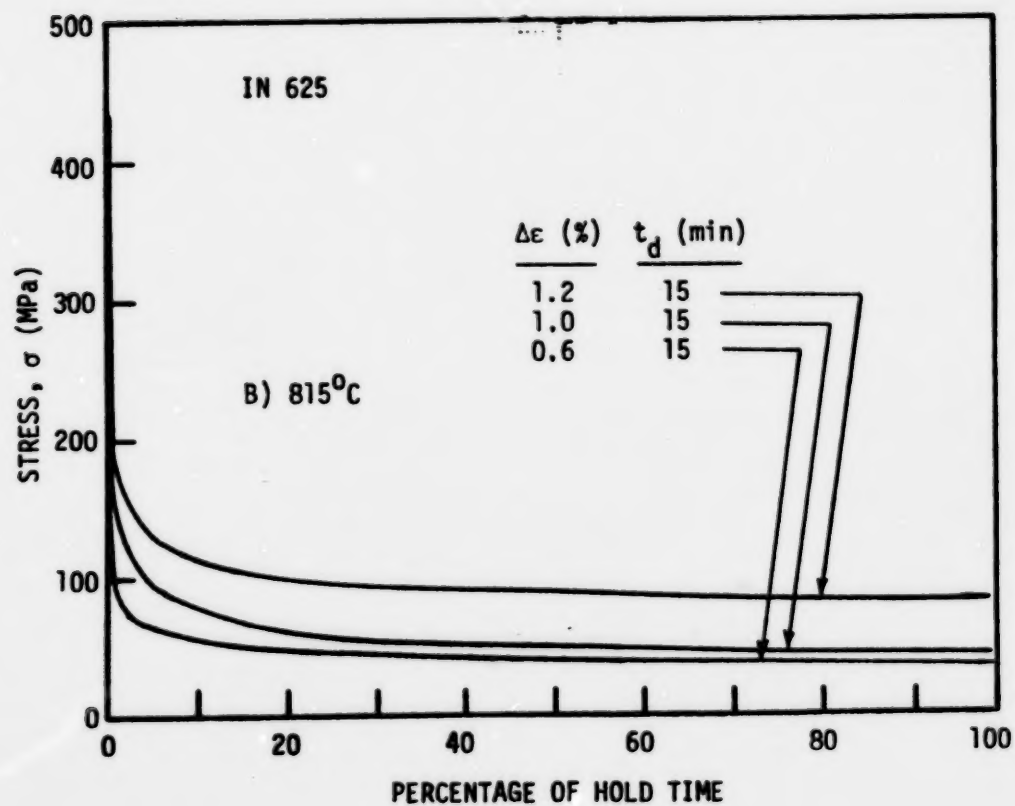
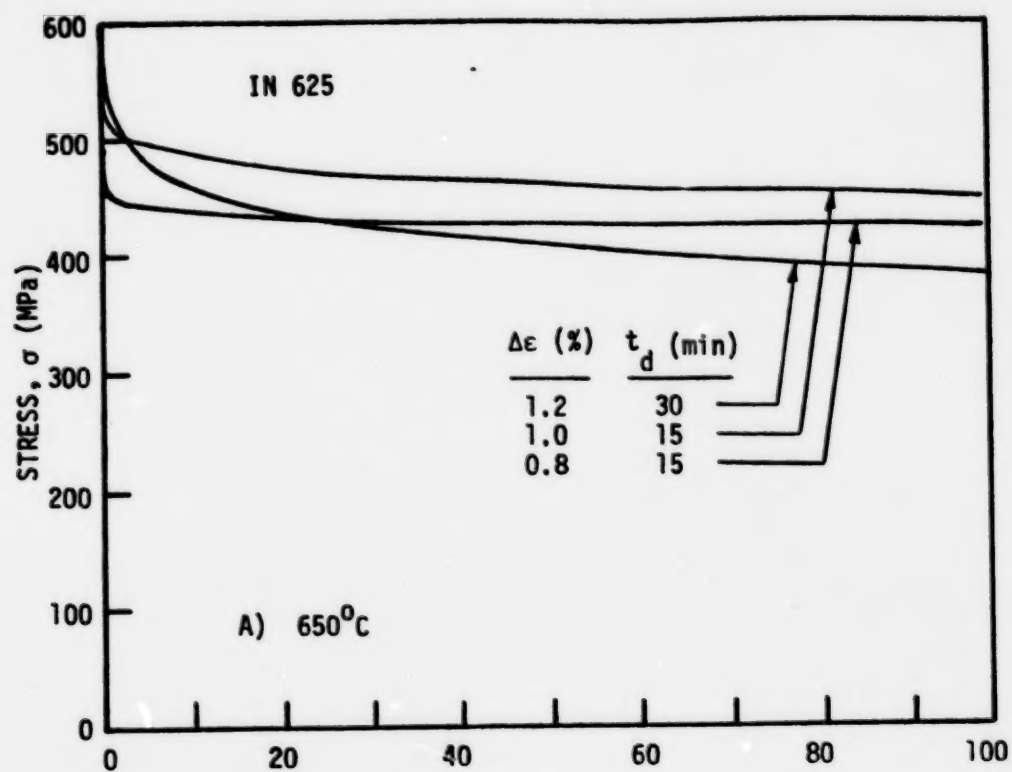


Fig. 3

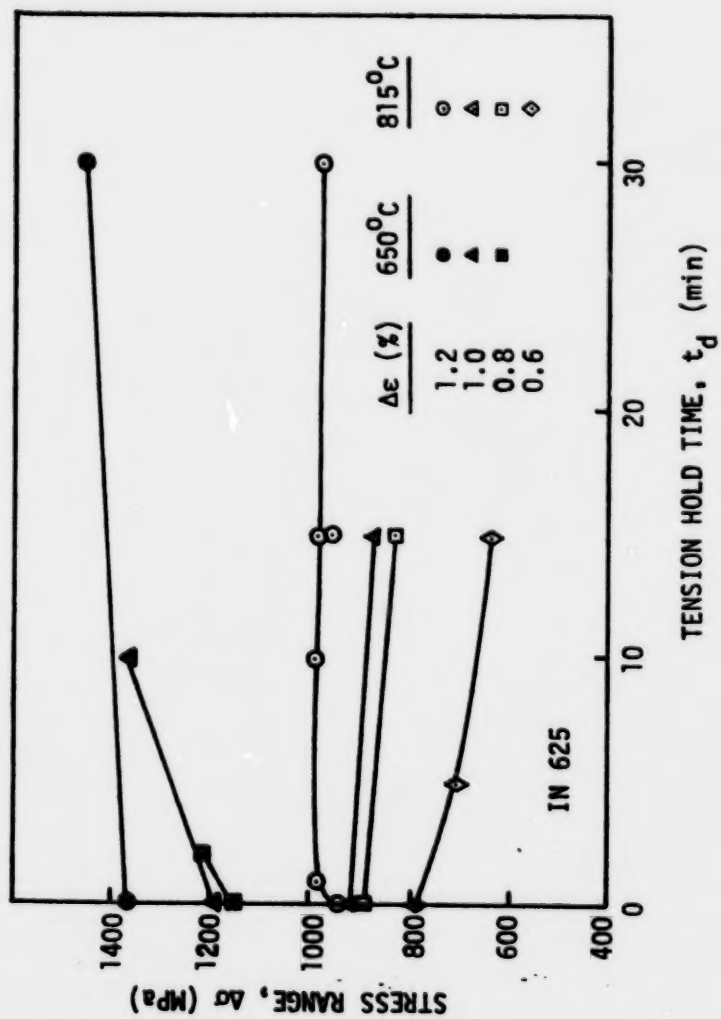


Fig. 4

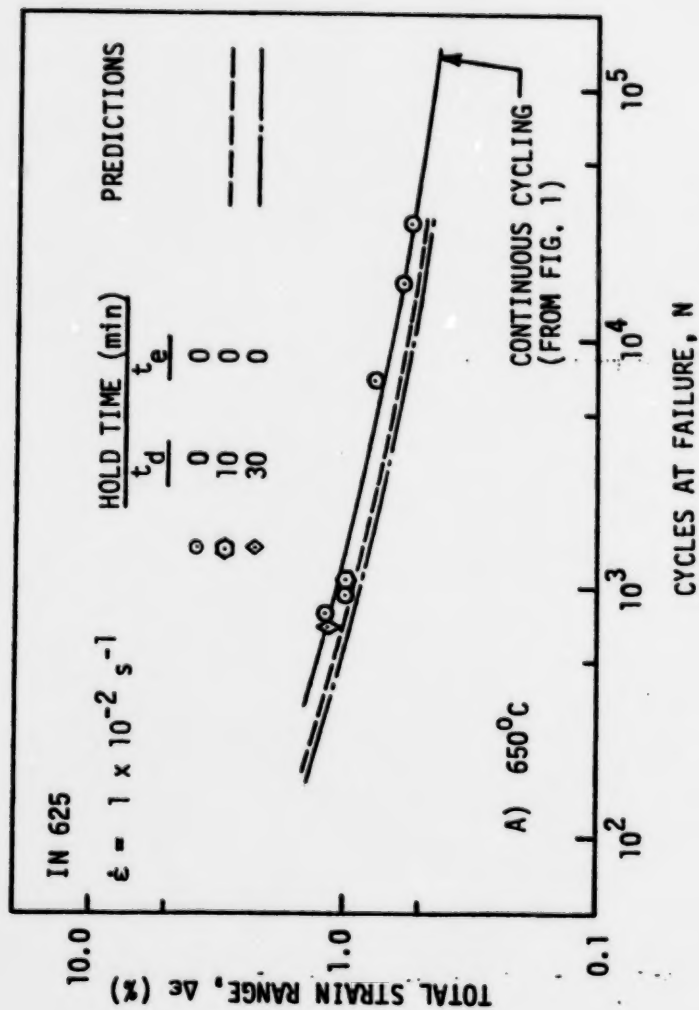


Fig. 5a

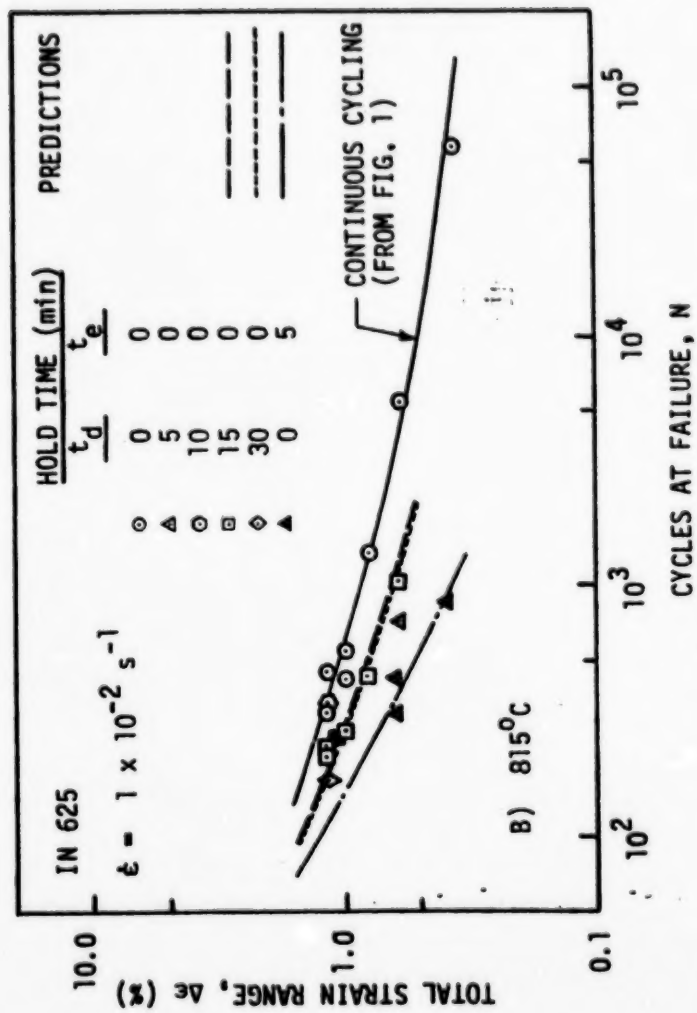


Fig. 5b

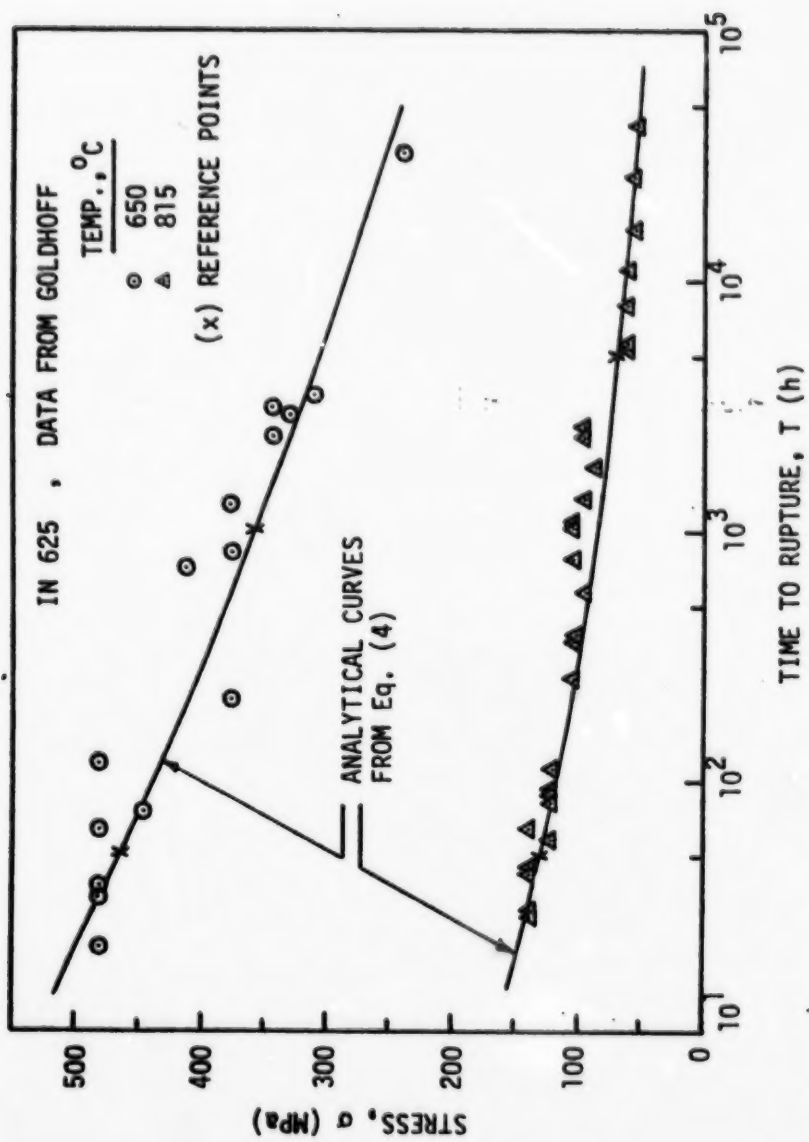


Fig. 6

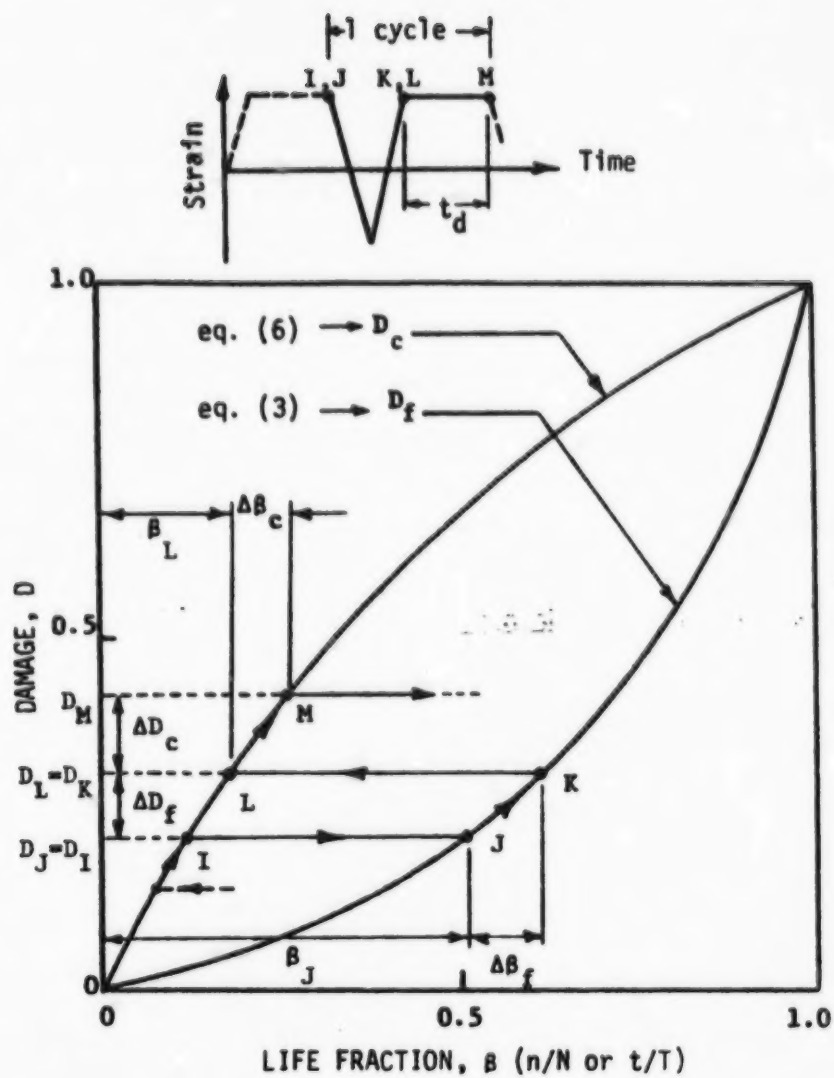


Fig. 7

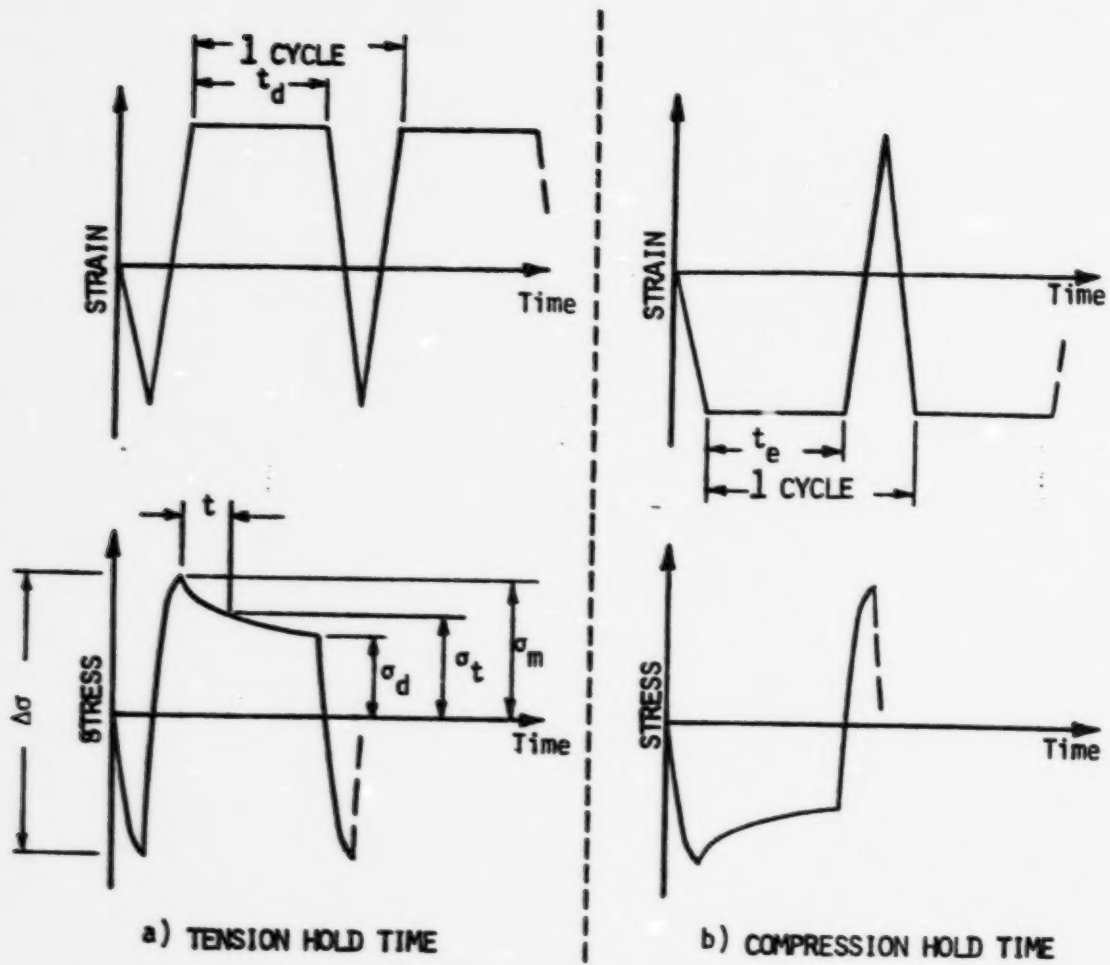


Fig. 8

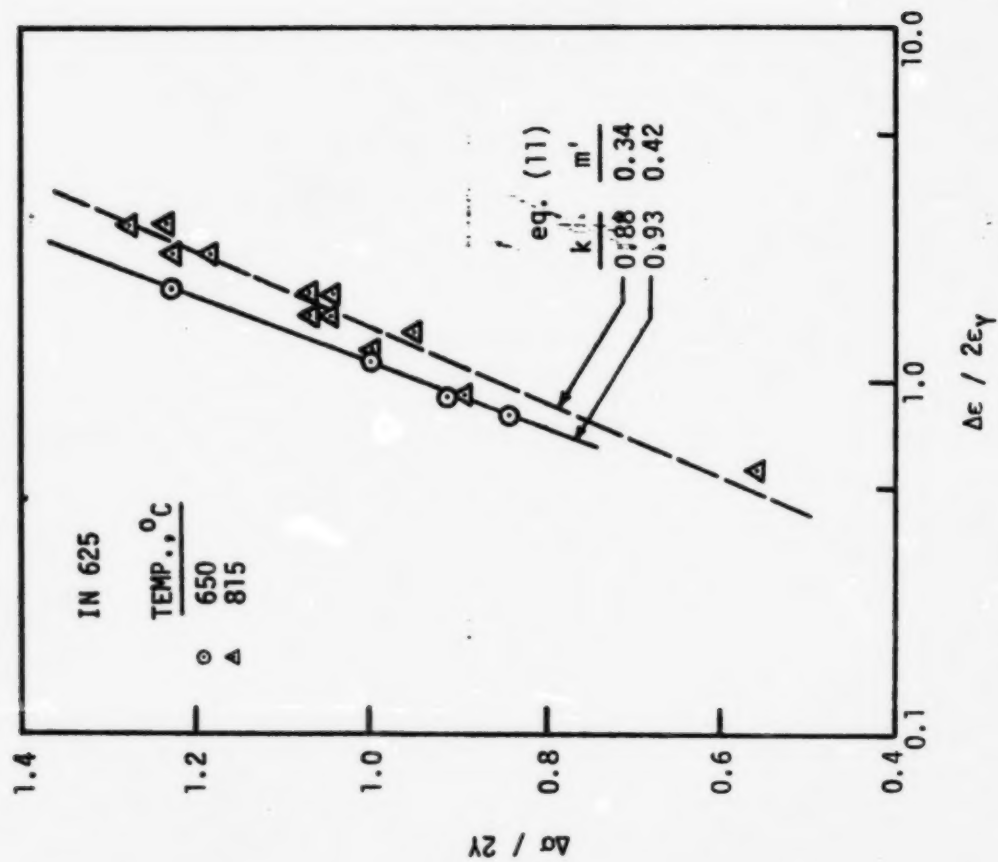


Fig. 9